Alternative EUV mask technology for Mask 3D effect compensation

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Reduction of mask3D effects by alternative mask technologies

Today: 0.33 NA

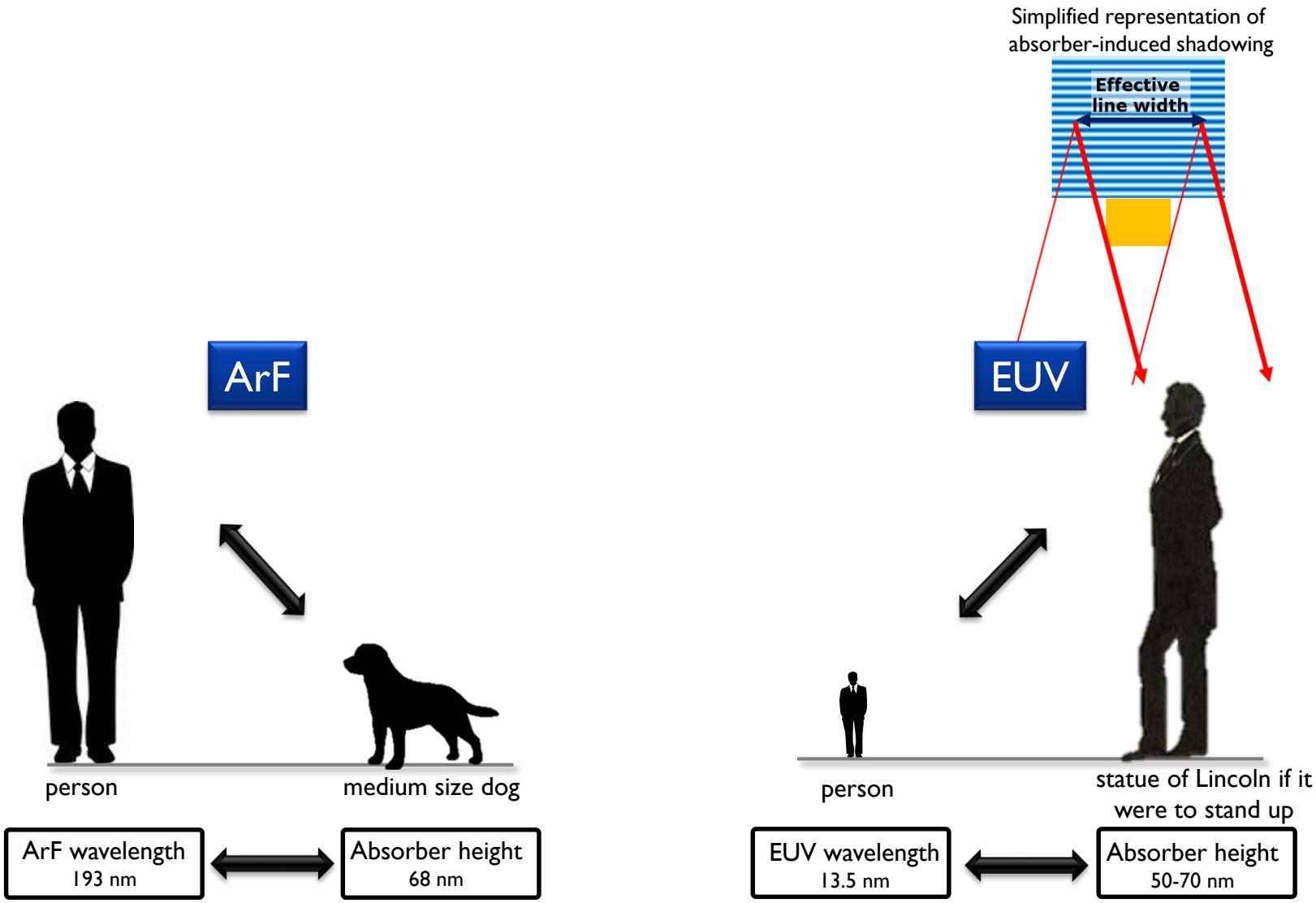
Tomorrow: ~0.50 NA

Towards experimental verification of alternative mask performance

Conclusion & Outlook

EUV Mask3D effects

A cause for HV differences, best focus and pattern shifts



EUV Mask3D effects

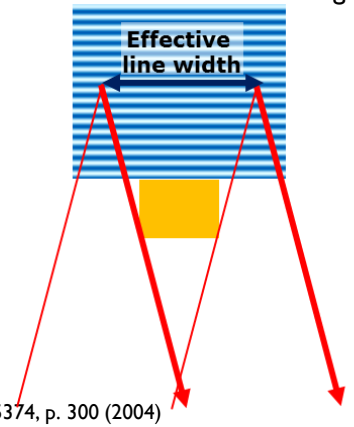
A cause for HV differences, best focus and pattern shifts

Mask3D effects in EUV:

~ caused by amplitude imbalance and phase errors in diffraction orders

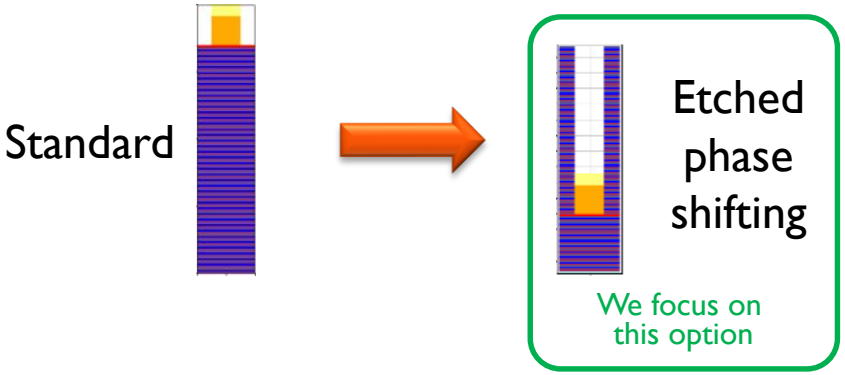
- H/V bias (both absorber and ML induced shadowing)
- Pattern shifts through focus
- Best Focus shifts through pitch
- NILS reduction

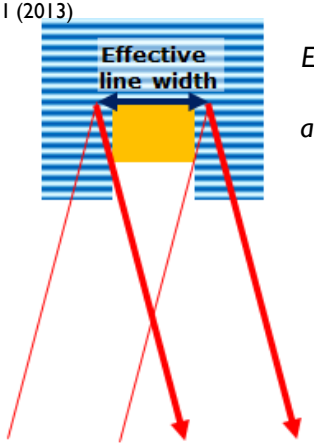
Simplified representation of absorber-induced shadowing



Promising alternative masks in literature*:

*B. La Fontaine *et al*, SPIE 5374, p. 300 (2004)
T. Schmoeller *et al*, SPIE 7379, 73792H (2007)
K. Takai *et al*., SPIE 8880, 88802M (2013)
A. Erdmann *et al*., SPIE 8679-61 (2013)



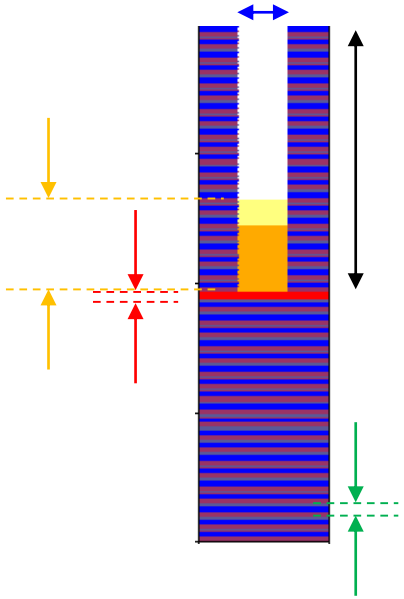


Effective width is closer to absorber width

Mask3D effects are inherent to current EUV mask technology & increase with mask incidence angle. Alternative masks have very different topography thus potentially less mask3D effects.

Optimization of Etched Phase Shifting Mask

Way of working



The Etched PSM has the following free parameters:

- Etch depth,
- Etch stop layer thickness,
- Absorber thickness (incl. oxide),
- Multi layer period,
- Mask CD.

*Note: tuning the absorber **material** is out-of-scope of this work, but could be a valuable extension of this work.*

⇨ We *optimize* these mask parameters based on NILS & Threshold (~1/Dose, ~throughput).

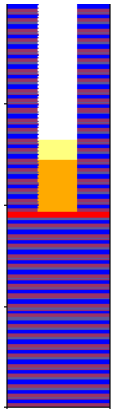
⇨ We then *evaluate* the performance of the optimized etched PSM for the mask3D specific effects :

- Overlapping Process Window, potentially limited by BF shifts through pitch
- Pattern shift through focus
- H/V bias (shadowing)

Optimization of Etched Phase Shifting Mask

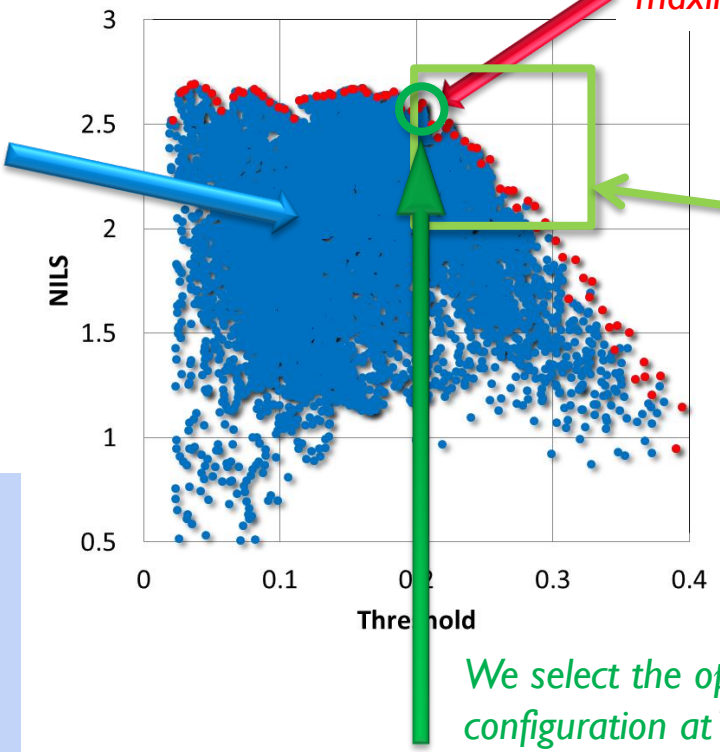
Mask parameters are optimized based on NILS

We fix the illumination conditions (NA, source shape) and wafer target, and then simulate the NILS & Threshold for all different mask geometries of the Etched Phase Shifting mask.



Each blue dot represents a combination of mask parameters.

Red dots represent the optimized parameter combinations with maximum NILS at each threshold.



Quadrant of interest
NILS > 2 & Threshold > 0.2
(≈ good imaging quality at reasonable exposure dose)

We select the optimized mask configuration at Threshold 0.2 for further evaluation.

Parameter variation example:
7 ML periods, ML factor from 0.98 to 1.04
20 Etch Depths, from 1 to 39 ML periods
14 Absorber thicknesses, from 0 to 269 nm
16 Etch stop layer thicknesses, from 0.5 to 8 nm
9 Mask CDs, from 8 to 16 nm
9 Defocus values, from -0.04 to 0.04 um

= ~2 500 000 parameter variations

Simulations done in S-Litho-EUV

Reduction of mask3D effects by alternative mask technologies

Today: 0.33 NA

Tomorrow: ~0.50 NA

Towards experimental verification of alternative mask performance

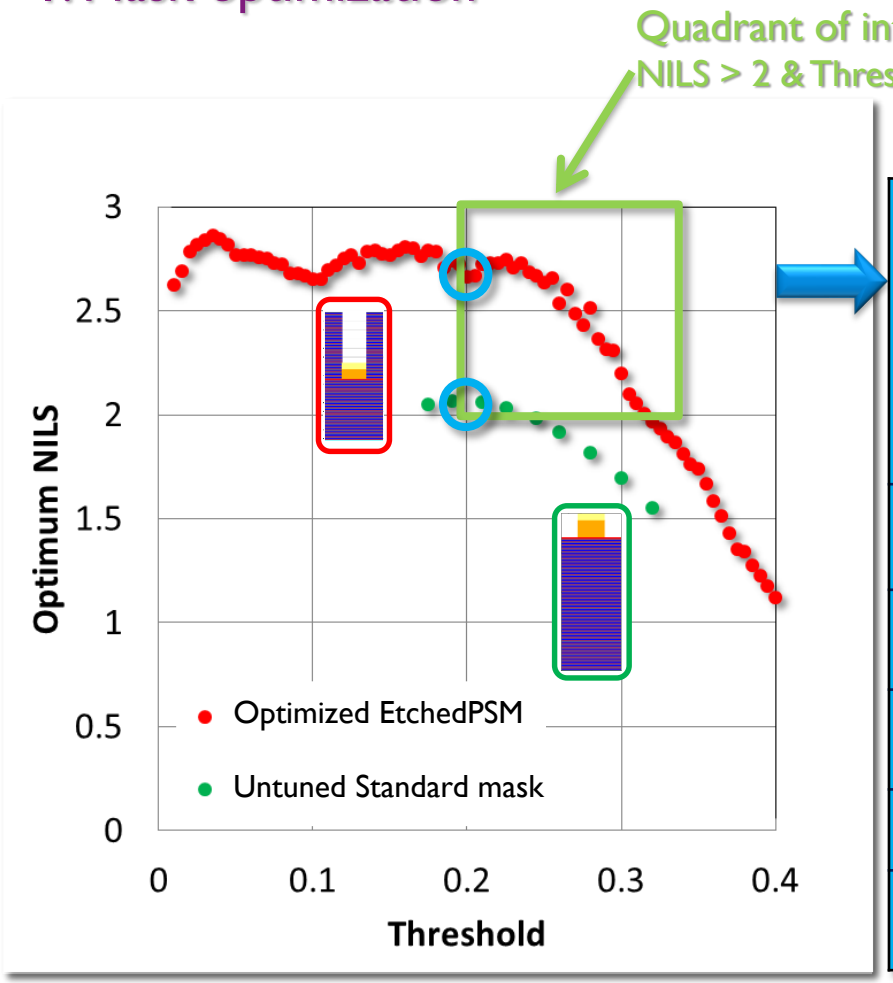
Conclusion & Outlook

Benefit of EtchedPSM at 0.33 NA

1. Mask optimization

NA 0.33, CRA 6°,4x,
CD 16 nm, Hor. P32

Dip90Y σ0.2-0.9



	Standard	EtchedPSM
ML Factor	1	1 (not optimized)
Etch Stop layer thickness (nm)	2.5	1
Absorber thickness (nm)	51	21
Mask CD (nm, 1x)	14.5	13
ML Etch depth (# ML periods)	-	21

We select the optimized mask parameters at Threshold 0.2 for the EtchedPSM at 0.33 NA. The Standard mask is not tuned.

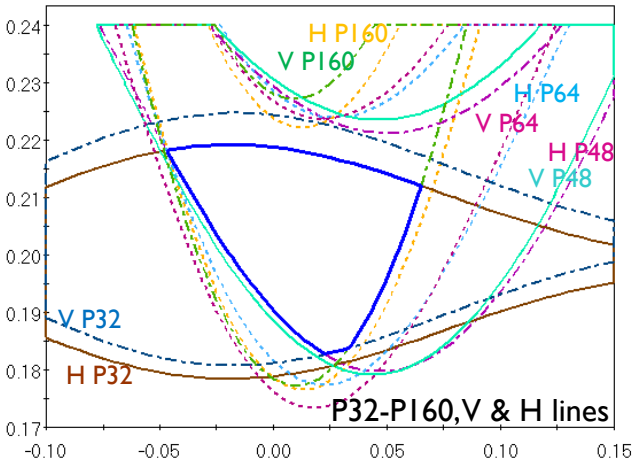
Benefit of EtchedPSM at 0.33 NA

2. Process Window evaluation for optimized mask

NA 0.33, CRA 6°,4x,
CD 16 nm, P32-P160

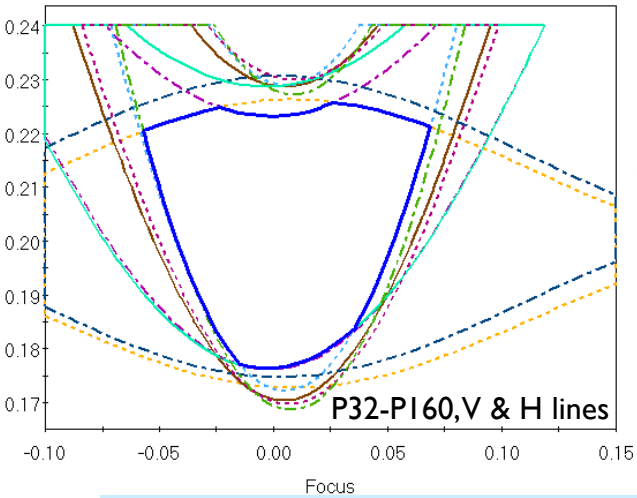
Dip90 σ0.2-0.9

Standard

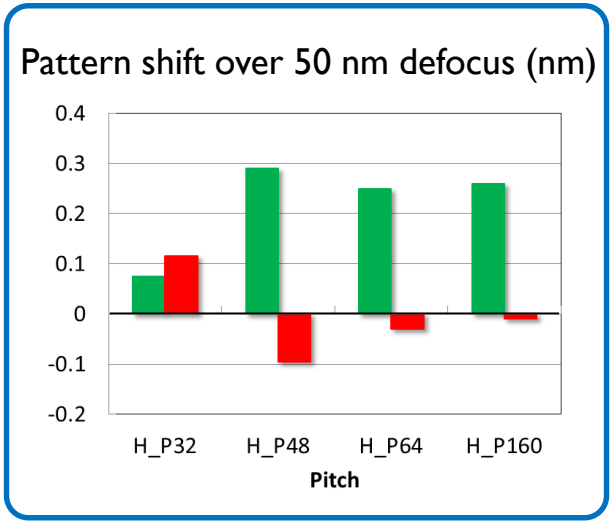


Max EL % & Max DoF
17.2 % & 100 nm

EtchedPSM



Max EL % & Max DoF
23.4 % & 125 nm



No pattern shift on vertical lines

Best Focus shifts are strongly reduced for the EtchedPSM compared to the Standard mask at 0.33 NA. This increases the overlapping process window by 35% in max EL and 25% in max DOF.
The EtchedPSM mask also has smaller pattern shifts through focus.

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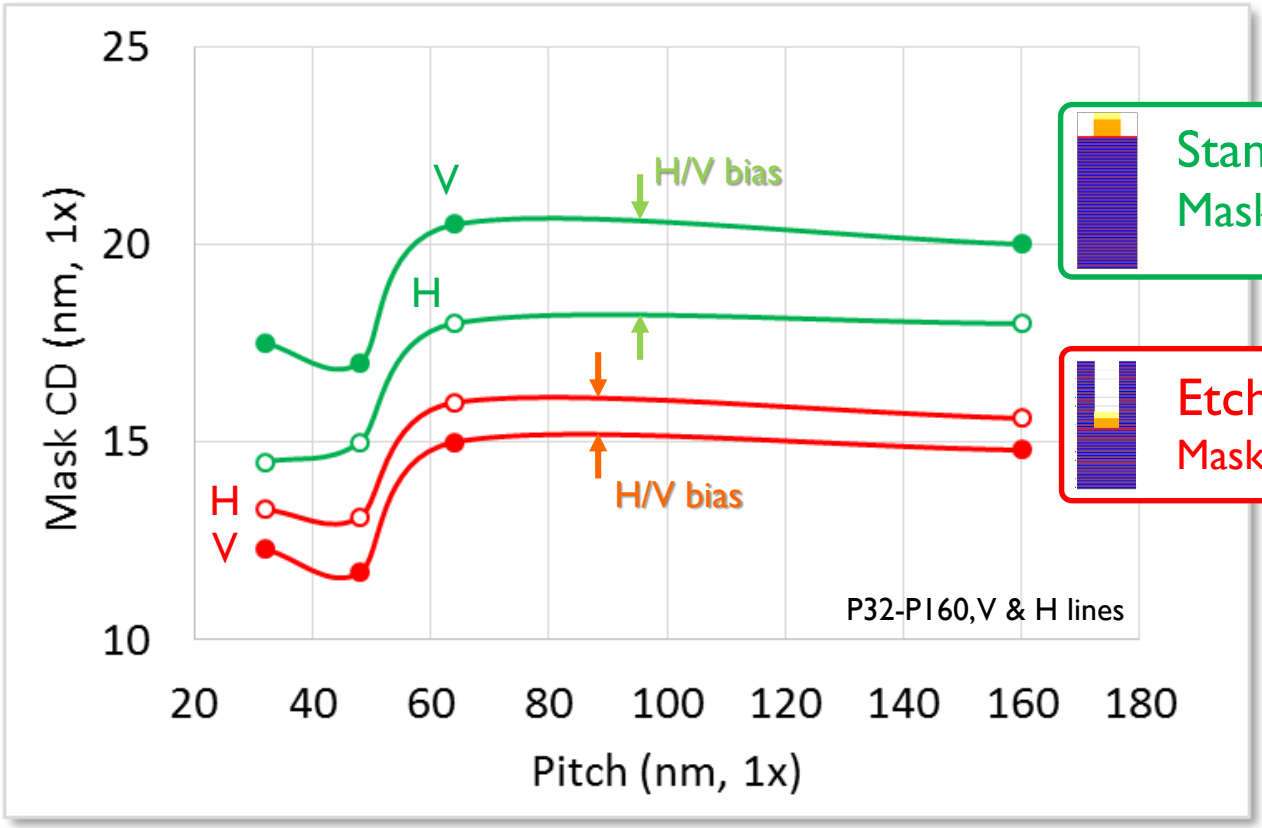
Benefit of EtchedPSM at 0.33 NA

3. H/V Bias evaluation for optimized mask

NA 0.33, CRA 6°,4x,
CD 16 nm, P32-P160

Dip90 σ0.2-0.9



Standard mask:
Mask H/V bias up to -3 nm (1x)

EtchedPSM:
Mask H/V bias ~1 nm (1x)

At 0.33 NA, the mask H/V bias is strongly reduced for the EtchedPSM compared to the Standard mask. Note the overall smaller mask CDs for the EtchedPSM.

Note: The ML etch depth determines the sign & value of the H/V bias. It could be further optimized.

Reduction of mask3D effects by alternative mask technologies

Today: 0.33 NA

Tomorrow: ~0.50 NA

Mag_x 4x, Mag_y 8x
6° CRAO

Towards experimental verification of alternative mask performance

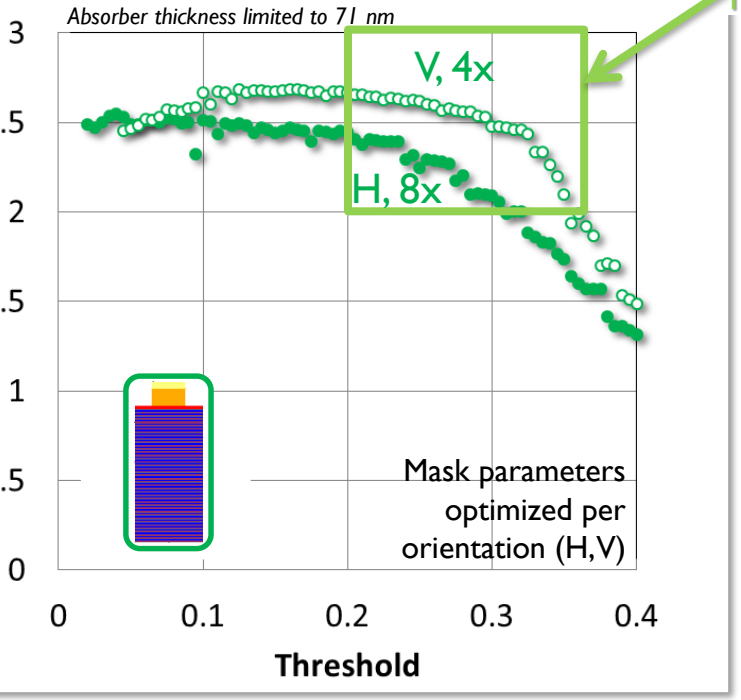
Conclusion & Outlook

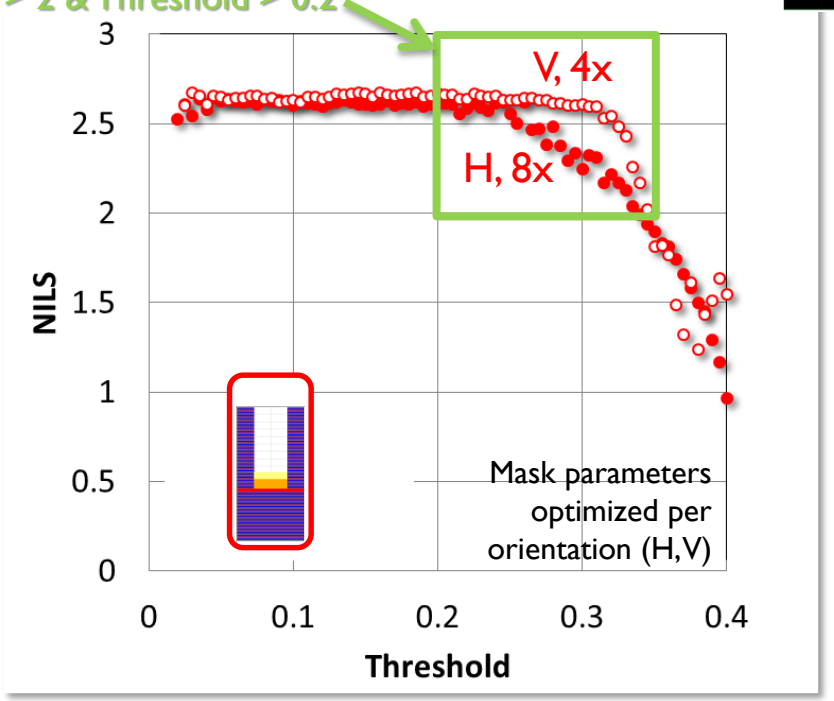
Benefit of EtchedPSM at 0.50 NA?

1. Mask optimization (*Is H still worse than V ?*)

NA 0.50, CRA 6°,
Mag_x 4x, Mag_y 8x,
CD 9 nm, P18

Leaf Dip σ0.6-0.99





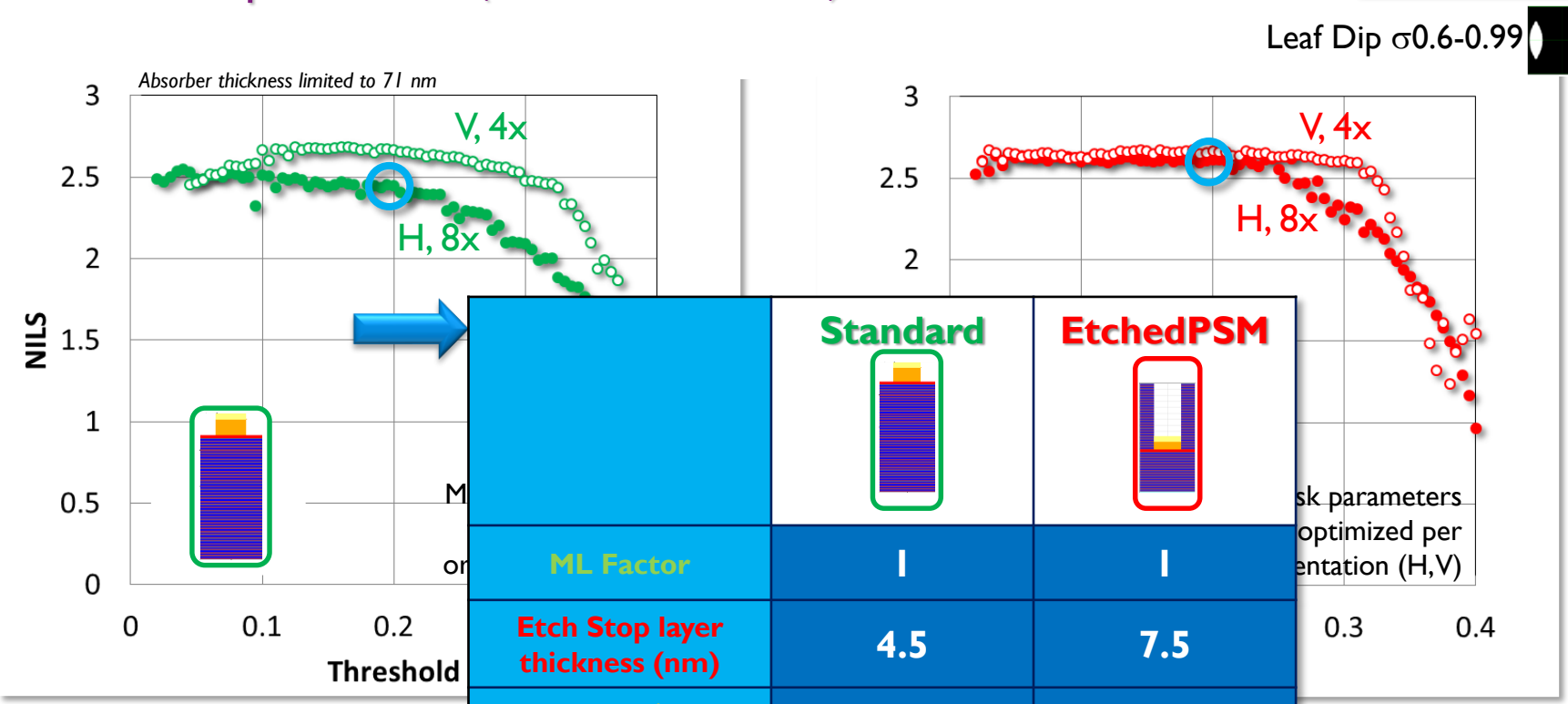
Both mask types show sufficiently high NILS to image P18 lines (V&H) at NA 0.50.

Benefit of EtchedPSM at 0.50 NA?

1. Mask optimization (*Is H still worse than V ?*)

NA 0.50, CRA 6°,
Mag_x 4x, Mag_y 8x,
CD 9 nm, P18

Leaf Dip σ0.6-0.99



	Standard	EtchedPSM
ML Factor	1	1
Etch Stop layer thickness (nm)	4.5	7.5
Absorber thickness (nm)	67	35
Mask CD (nm,1x)	8	9
ML Etch depth (# ML periods)	-	25

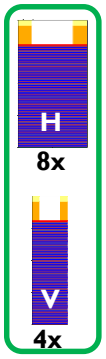
Both mask types show sufficiently high NILS to image P18 lines (V&H) at NA 0.50.
We select the mask parameters at Threshold 0.2 from the optimization of the horizontal lines, as this orientation has slightly lower NILS.

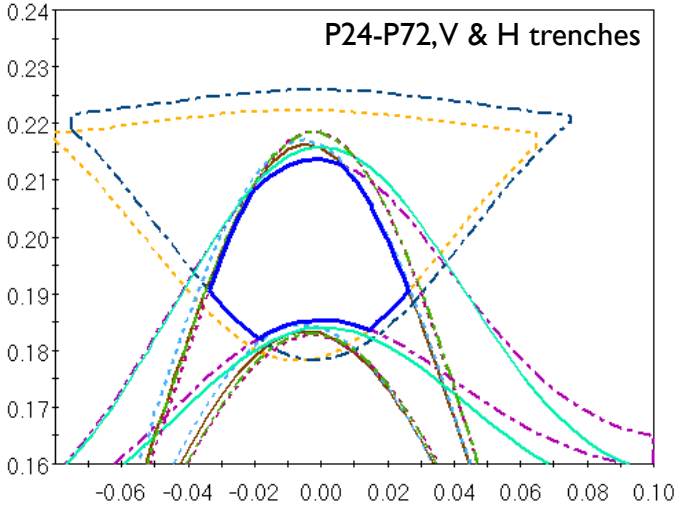
Benefit of EtchedPSM at 0.50 NA

2a. Process Window evaluation for optimized mask

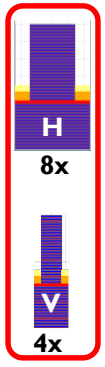
NA 0.50, CRA 6°,
Mag_x 4x, Mag_y 8x,
CD 12 nm, P24 - P72

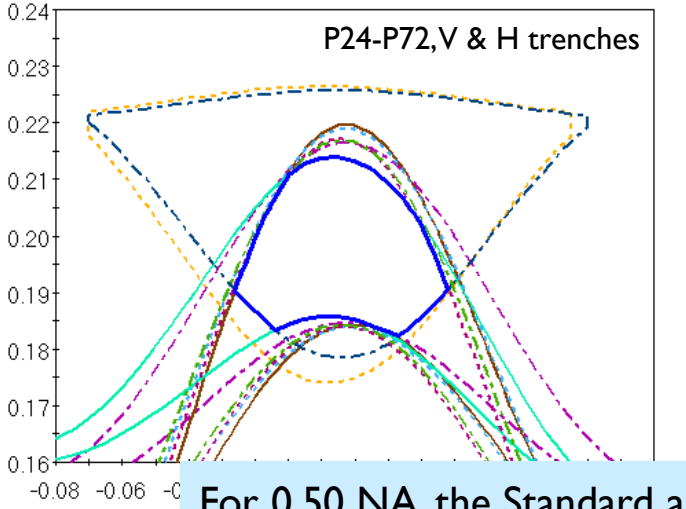
Freeform source 



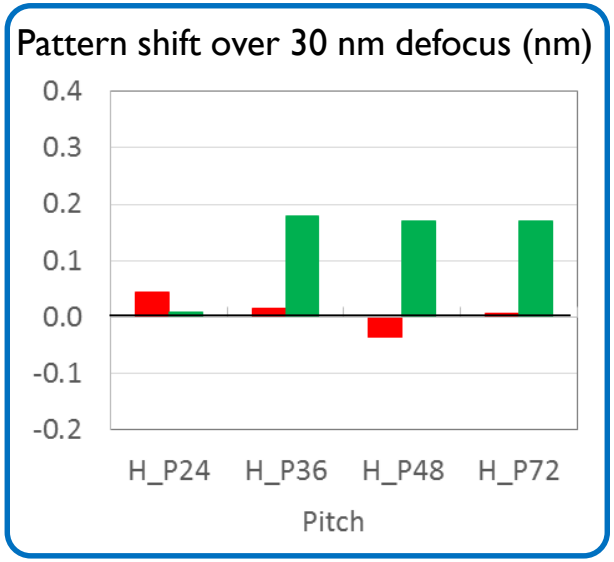


Max EL % & Max DoF
14.2 % & 60 nm





Max EL % & Max DoF
14.1 % & 64 nm



For 0.50 NA, the Standard and EtchedPSM show very similar overlapping PWs and no BF shifts. For the EtchedPSM, the pattern shifts through focus are clearly better than for the standard mask.
Can reducing the absorber thickness of the standard mask improve the pattern shift?

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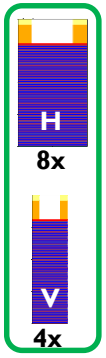
Benefit of EtchedPSM at 0.50 NA

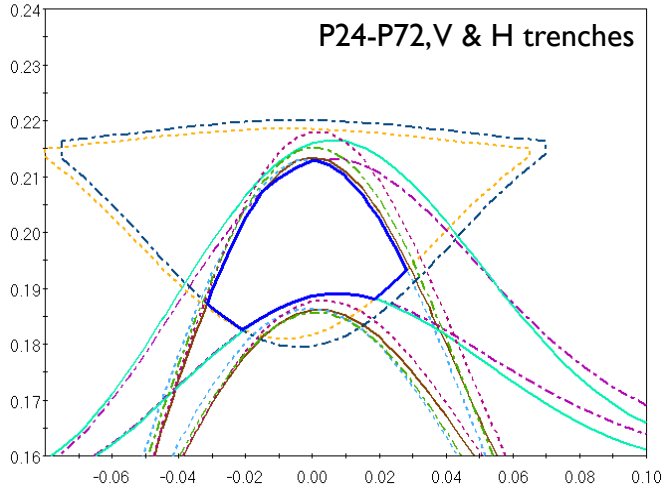
2b. Process Window evaluation for optimized mask

NA 0.50, CRA 6°,
Mag_x 4x, Mag_y 8x,
CD 12 nm, P24 - P72

Freeform source 

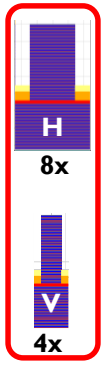
51 nm absorber

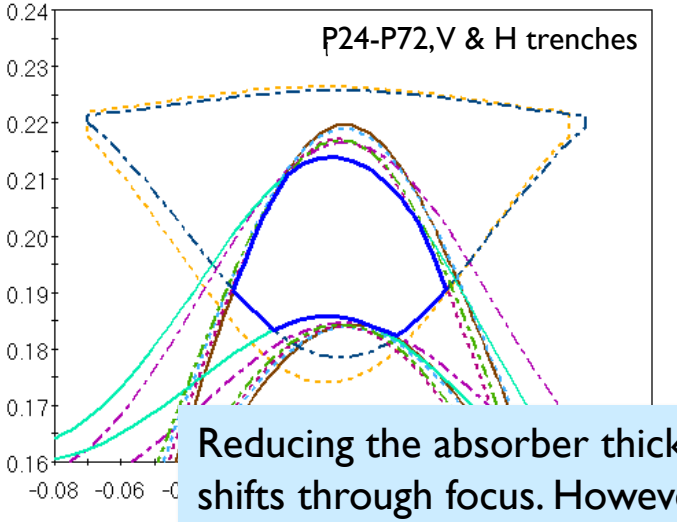




Thinner absorber 51 nm

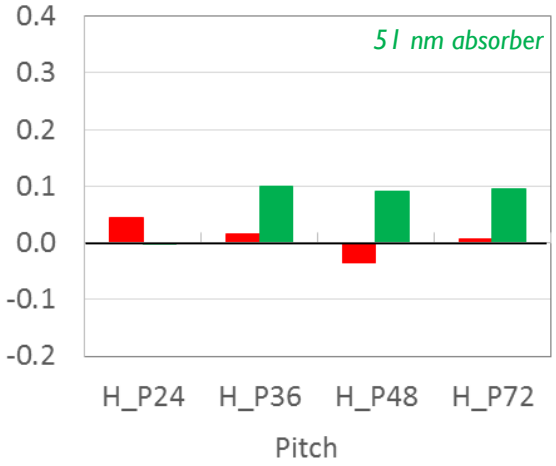
Max EL % & Max DoF
12.0 % & 55 nm





Max EL % & Max DoF
14.1 % & 64 nm

Pattern shift over 30 nm defocus (nm)



Reducing the absorber thickness for the standard mask reduces (=improves) the pattern shifts through focus. However, as expected, the trade-off is that the PW performance shrinks.
For the **EtchedPSM, this trade-off is not present**, and good process window performance and absence of pattern shifts through focus are obtained at the same time.

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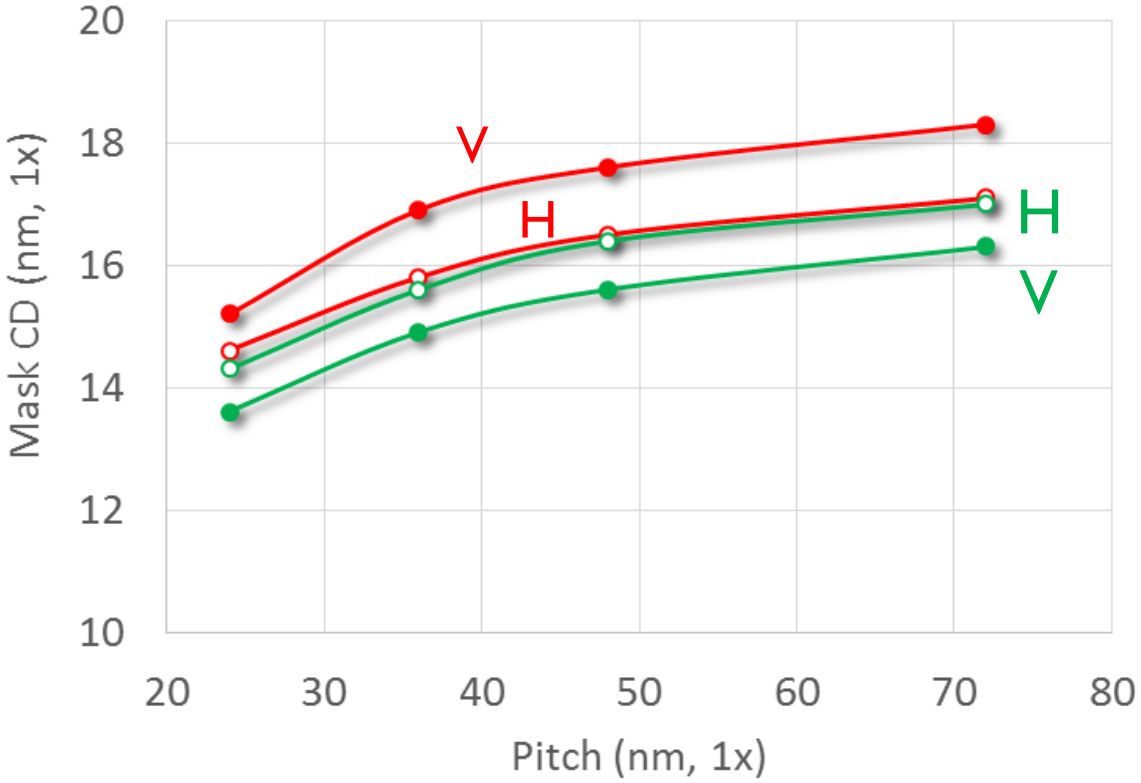
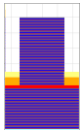
Benefit of EtchedPSM at 0.50 NA ?

3. H/V Bias evaluation using optimized mask

NA 0.50, CRA 6°,
Mag_x 4x, Mag_y 8x,
CD 12 nm, P24 - P72

Freeform source 





EtchedPSM:
Mask H/V bias ~ -1 nm

Tuned Standard mask:
Mask H/V bias ~ 1 nm
67 nm absorber

For 0.50 NA, both the standard and the EtchedPSM have a small H/V bias of ~1 nm (1x).

Note: The ML etch depth determines the sign & value of the H/V bias. It could be further optimized.

Comparison of EtchedPSM to Standard Mask

Summary of simulation results

Today 0.33 NA

EtchedPSM provides a *nice-to-have gain* wrt the standard mask in NILS, BF and pattern shifts, OPW & HV bias

Tomorrow ~0.50 NA

Mag_x 4x, Mag_y 8x

Both the standard and EtchedPSM show good imaging performance in terms of NILS & oPW with only small H/V bias & no BF shifts.

However, the EtchedPSM provides a gain wrt the standard mask in the sense that there is no trade-off between PW performance and pattern shift through pitch. Both can be optimized at the same time.

Reduction of mask3D effects by alternative mask technologies

Today: 0.33 NA

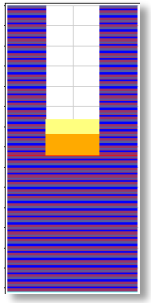
Tomorrow: ~0.50 NA

Towards experimental verification of alternative mask performance

Conclusion & Outlook

Towards exp. verification of alternative mask performance

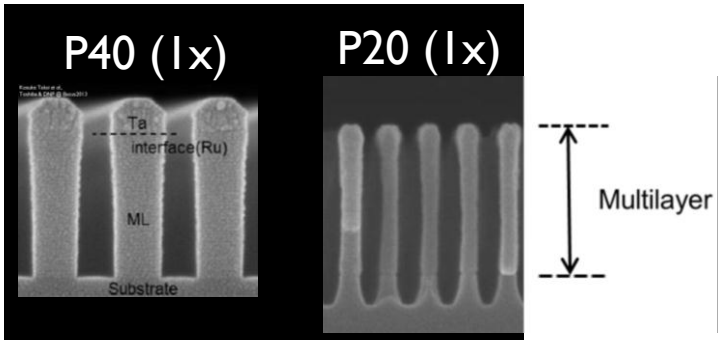
Challenges



- ML Patterning: Sidewall angle control, high aspect ratio
- Deposition of absorber material after ML patterning
- Mask Cleaning: Damage to the exposed multi-layer sidewall, pattern collapse

Encouraging progress in literature

Kosuke Takai *et al.*,
Toshiba & DNP, 88802M @ Bacus2013



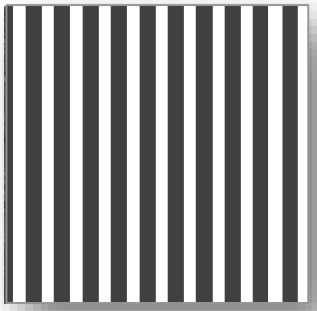
Successfull multi-layer etch at resolution reported.

Although there is no absorber present in this mask architecture, it is a valuable first step to establish proof of concept.

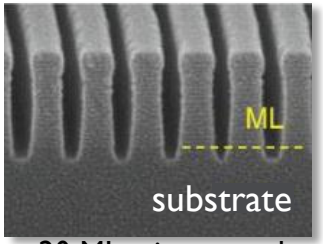
Towards exp. verification of alternative mask performance

Etched ML mask is ready for proof of concept experiments on NXE3300

P20 (1x) line/space



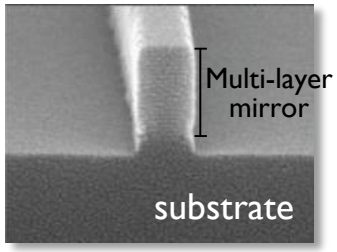
P20 (1x) line/space x-section



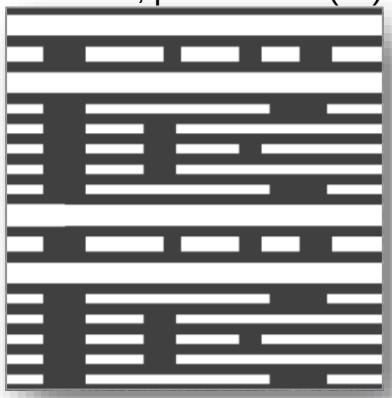
20 ML mirror used to ensure cleanability without pattern collapse

P96CD20 (1x) space

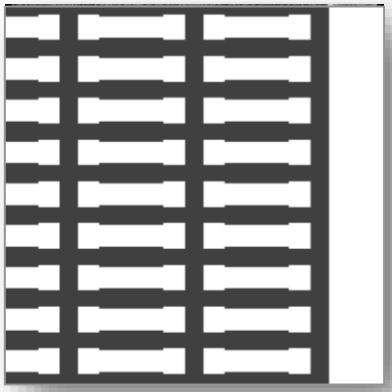
ISO CD20 (1x) space x-section



N7 Metal, pitch 28 nm (1x)



Gap 18 nm on P40CD20 trenches (1x)



Mask developed by Toshiba and DNP and supplied by DNP (DTF)

Joint project

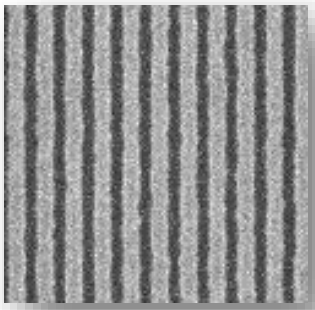
DNP
TOSHIBA
ASML
imec

An Etched ML mask is designed and fabricated to experimentally verify the improvement in mask 3D related imaging effects (HV bias, BF shifts, pattern shift through focus).
Reticle SEM images show good pattern fidelity, MTT and linearity.

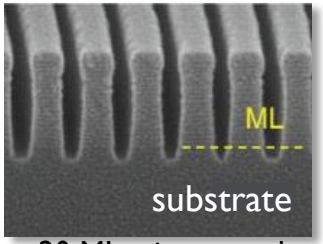
Towards exp. verification of alternative mask performance

Etched ML mask is ready for proof of concept experiments on NXE3300

P20 (1x) line/space

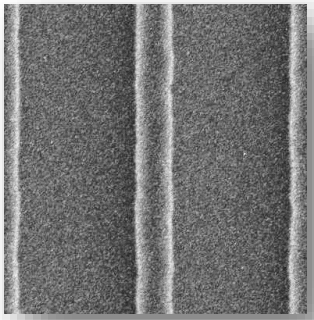


P20 (1x) line/space
x-section

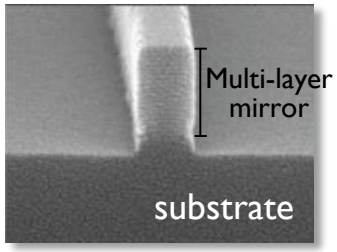


20 ML mirror used
to ensure cleanability
without pattern collapse

P96CD20 (1x) space



ISO CD20 (1x) space
x-section



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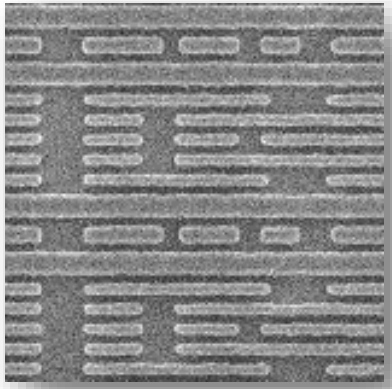
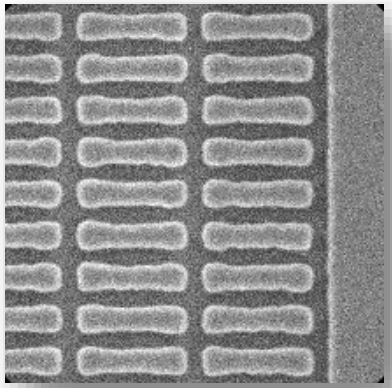


Gap 18 nm on P40CD20 trenches (1x)



Joint project

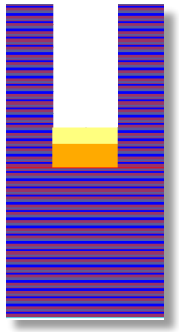
DNP
TOSHIBA
ASML
imec

Mask developed by Toshiba and DNP and supplied by DNP (DTF)

An Etched ML mask is designed and fabricated to experimentally verify the improvement in mask 3D related imaging effects (HV bias, BF shifts, pattern shift through focus).
Reticle SEM images show good pattern fidelity, MTT and linearity.

Conclusion & Outlook

In simulations, the Etched Phase Shifting Mask shows improved imaging performance compared to the Standard (=Ta-based) Mask:

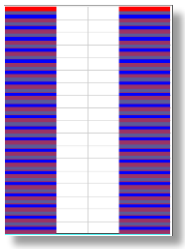


16 nm hp
Practical resolution limit

- for **0.33 NA**, we find a nice-to-have gain in NILS, Best Focus and pattern shifts through focus, overlapping Process Window & HV bias,

9 nm hp

- for **0.50 NA**, both masks shows similar good performance for NILS, Best Focus shifts and H/V bias. The EtchedPSM provides gain in pattern shifts through focus.



Technological mask making/cleaning challenges ⇨ encouraging progress which has led to the fabrication of a high-quality prototype Etched multi-layer mask.

The ambition is to verify the benefit of the Etched multi-layer mask on wafer and provide proof of concept for the improved imaging performance of Etched ML EUV mask architectures for mask 3D related effects.

Thanks !

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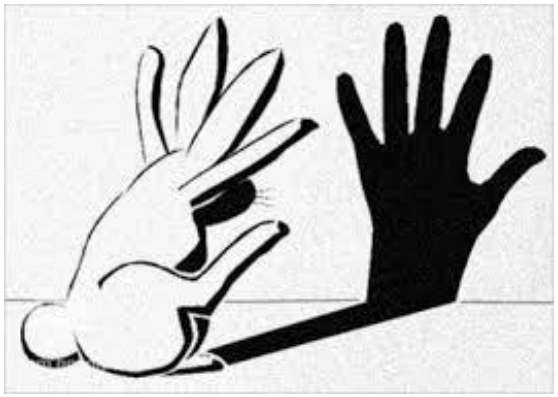
Geert Vandenberghe, Kurt Ronse (imec)

Gerardo Bottiglieri, Laurens de Winter, Roel Knops, David Rio (ASML)

Weimin Gao (Synopsys)

... and to you for listening



Shadowing...
not only an EUV challenge